5 Technology Development

The technology program must meet three challenges — nanometer-level control and stabilization of optical elements on a lightweight flexible structure, picometer-level sensing of the relative position of optical elements over distances as large as 10 meters, and integration, testing, and in-orbit operations of a complex system. The technology development program is led by the Jet Propulsion Laboratory in collaboration with the two industry partners, Lockheed Martin Missiles and Space in Sunnyvale, California, and TRW Inc., Space and Electronic Group in Redondo Beach, California.

Optical double corner cubes form the fiducial metrology points defining the length of the interferometry baselines. Vertices are aligned to better than 1 μm, as in this prototype.

Our approach to technology development is that of rapid prototyping of critical hardware and software, followed by integration into ground-based technology testbeds. In these testbeds, critical interfaces will be validated, system-level performance demonstrated, and integration and test procedures developed and verified. To complete the technology development by the end of 2001, some hardware components will be developed in parallel with the testbeds.

This approach places the ground testbeds at the very heart of the technology development effort. It is in these testbeds that our engineering team will learn what works and what does not work when it comes to integrating and testing interferometers. Flight experiments will be undertaken only when the space environment is required.

The accompanying table (see next page) summarizes the suite of required technologies for SIM.

Component Hardware

Breadboards and brassboards of the new-technology components will be built and tested in close collaboration among JPL and industry partners. "Breadboards" are prototypes that use off-the-shelf laboratory components to demonstrate technical feasibility. In contrast, "brassboard" systems use components that match at least the dimensions, power, and environmental requirements of the final instrument hardware, where individual components may or may not be flight qualified. The objectives are threefold: to mitigate technical, schedule, and cost risk associated with key hardware components early in the SIM project life cycle (when

TECHNOLOGIES

Required technologies for SIM.

REQUIREMENT	TECHNOLOGIES
Nanometer stabilization	Controlled optics; steering mirrors and delay lines; vibration isolation and structural quieting; precision deployable structures
Picometer sensing	Laser metrology; astrometric and nulling starlight fringe detection
Integration and test	End-to-end integration, test, and operation of interferometers; integrated modeling of optical, mechanical, and thermal control

the cost of correcting problems is low); to deliver necessary components to the technology integration testbeds; and to transition the capability to manufacture these components to industry.

For brassboarding each component, a series of performance and environmental tests will be conducted whose objective will be to qualify the component design as ready for space flight. A distinction is made between qualifying the design and qualifying the component itself. None of the brassboard components are destined for flight; hence, the qualification process will lack the formality and cost associated with flight hardware. Nevertheless, the qualification process will be quite rigorous, with each component subjected to full functional, shock, random vibration, and thermal–vacuum testing. JPL quality assurance and reliability personnel will be included from the outset to ensure proper test procedures. Only those components considered to be high risk will be built and tested as brassboards.

Real-Time Software

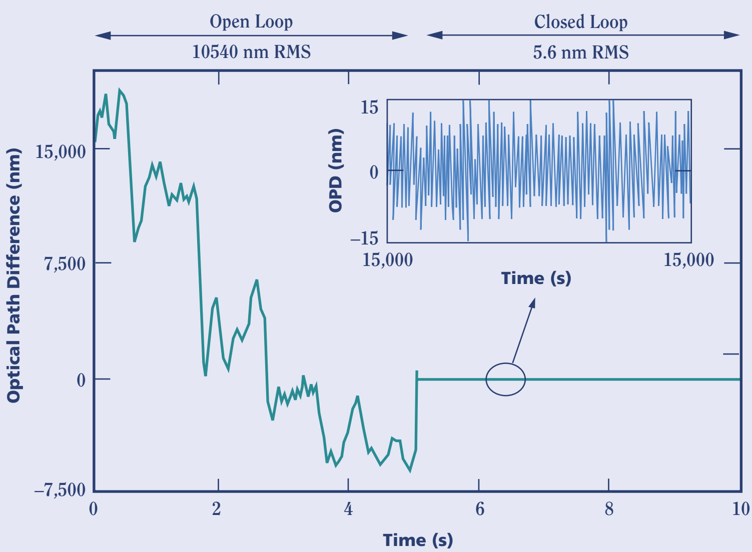
The SIM instrument will need to operate with limited intervention from the ground, and therefore must perform important functions with a high level of autonomy. These functions include initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, slew, and rotation. Real-time software will play the central role in performing these functions. The software will have to operate a complex instrument run on a distributed set of computers, and must control processes on timescales from milliseconds to days. Such an advanced system demands sophisticated software, and its portion of

DELAY LINE
Brassboard optical delay line.

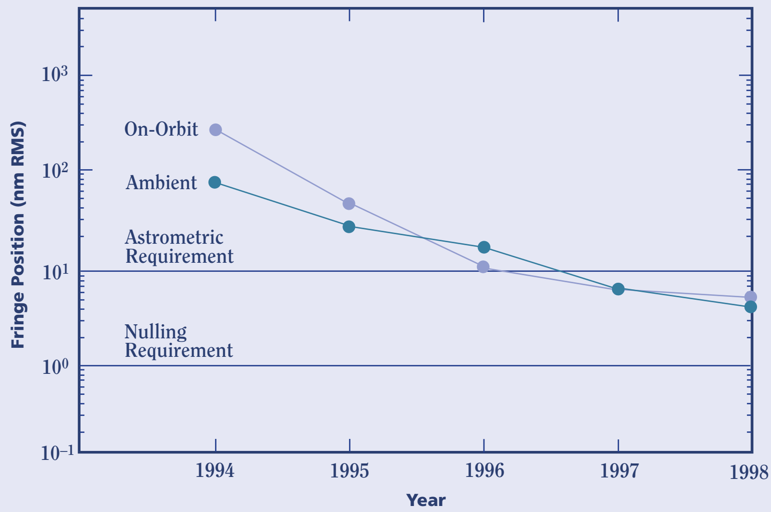
BEAM COMBINER
Brassboard astrometric beam combiner.

The SIM System Testbed (STB) is an evolutionary series of two testbeds. The first, STB-1, was built during FY'91 through FY'94. STB-1 is a full single-baseline interferometer built on a flexible structure using breadboard hardware. The structure is an aluminum truss, $7 \times 6.8 \times 5.5$ meters in size, with a mass of 200 kilograms. With optics and control systems attached, the total mass is about 600 kilograms. Three active gravity off-load devices form the structure's suspension system, providing about a factor of 10 separation between the structure's rigid-body and flexible-body modes, the lowest of which is at about 6 hertz. The equipment includes a three-tier optical-delay line with associated laser metrology, a pointing system complete with two gimballed siderostats, two fast-steering mirrors, coarse- and fine-angle tracking detectors, a six-axis isolation system, and all associated electronics and real-time computer control hardware necessary for closed-loop system control and data acquisition.

The principal objectives of STB-1 are to demonstrate vibration-attenuation technologies and validate the Integrated Modeling of Optical Systems (IMOS) modeling tool in the nanometer regime. STB-1 was completed in summer 1994, when "first fringes"



Fringe Tracking. *Time trace of STB-1 fringe tracking optical path difference with control loops open and closed.*



Evolution. *Historical improvement in STB-1 ambient and emulated "on-orbit" metrics.*

were acquired. Two metrics have been tracked over time to monitor testbed progress: (1) pseudo-star fringe-tracking stability in the presence of the laboratory ambient vibration environment, and (2) fringe stability versus emulated spacecraft reaction wheel disturbances, expected to be the dominant on-orbit disturbance source. The goal is to achieve 1 nanometer by the end of the evolutionary STB program.

The second testbed (named STB-3 for historical reasons) will essentially be a new build from the ground up. The goal for STB-3 is to build a testbed whose operational complexity approaches that of the flight instrument.

project cost and associated schedule and cost risk begins to rival that of hardware. Thus, the technology team has placed the importance of the development of real-time software on a par with that of interferometer hardware.

The development of real-time software is completely analogous to the development of component hardware via breadboards and brassboards. Breadboard software is regarded as code that establishes the feasibility of performing a particular function. Brassboard software is a

> **IMOS enables end-to-end modeling, in a single-workstation environment, of complex optomechanical systems.**

true prototype of flight software; it will demonstrate that the constraints imposed by the flight processor can be met and that the code is efficient and maintainable. The brassboard software developed under the technology program could actually be flown on SIM with only minor modifications and upgrades.

Development of the SIM breadboard software is, to a large extent, already done. This is due to the recent development of two ground interferometers: the Palomar Testbed Interferometer and the evolutionary SIM System Testbed. Both share a significant amount of real-time software and together demonstrate the basic feasibility of automated interferometer operation.

The code for the SIM brassboard software will be built in modules in a series of incremental deliveries, greatly simplifying the testing and debugging process. The initial deliveries will be internal to the development team and will serve to validate the development approach and train the personnel. Testing will incorporate breadboard and brassboard hardware to actually drive the relevant controlled components. Eventually, the software will be delivered to the integration testbeds, where it will be used to operate complete interferometers.

Integrated Modeling

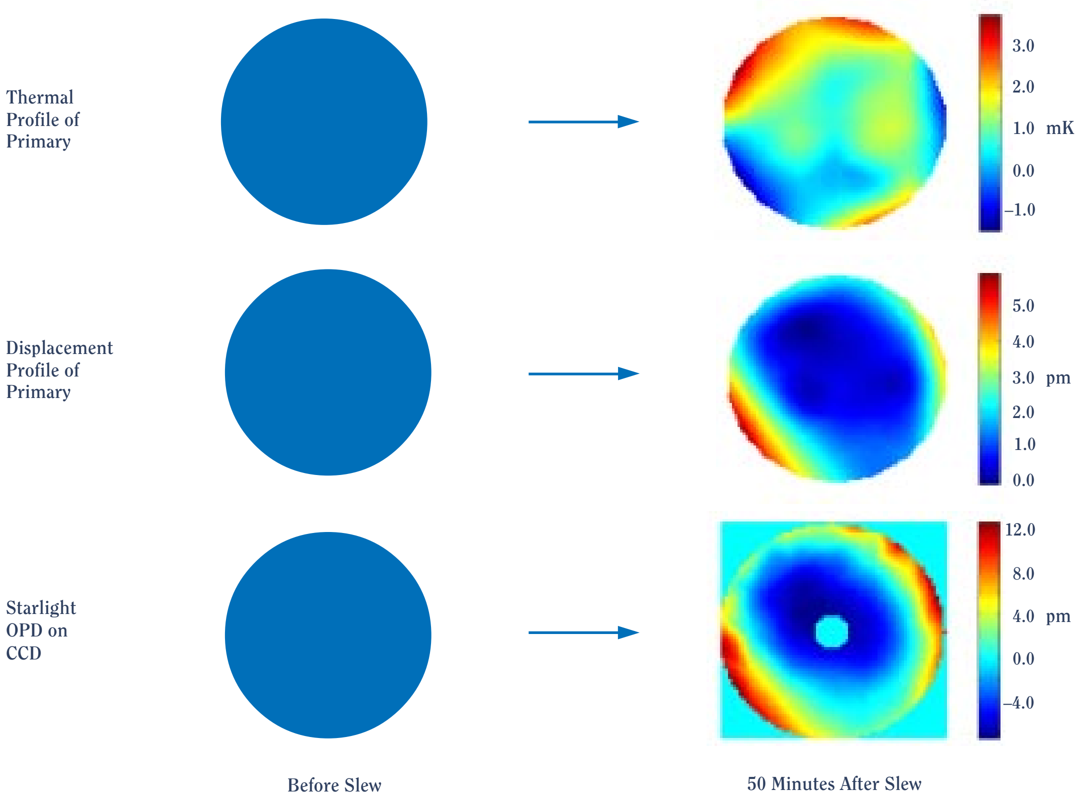
Development of advanced software tools is required to aid in the design of spaceborne interferometers. Existing tools determine optical performance from the geometry and material properties of the optical elements in the system, assuming only minor deviations from the nominal alignment and figure. These tools cannot evaluate the impact on optical performance from controlled and articulated optics, structural dynamics, and thermal response — important considerations for future interferometer missions.

To investigate these critical relationships, a new analysis tool has been developed called Integrated Modeling of Optical Systems (IMOS). IMOS enables end-to-end modeling, in a single-workstation environment, of complex optomechanical systems — including optics, controls, structural dynamics, and thermal analysis. IMOS has been applied at JPL to the Hubble Space Telescope and the Space Infrared Telescope Facility, as well as to virtually all the space interferometer designs that have been considered in recent years.

IMOS was originally created as a modeling tool to assist in the early design phases of multidisciplinary systems. It has matured tremendously and has greatly increased its ability to address complex, many-degrees-of-freedom systems that are typical of the detailed design phase. Currently, IMOS is also the baseline integrated modeling tool for the Next Generation Space Telescope pre-project.

Ground Integration Testbeds

Three ground testbeds are planned to demonstrate that all components fit together and work as an interferometer at the required level of performance: the evolutionary SIM System Testbed, the Microarcsecond Metrology Testbed, and



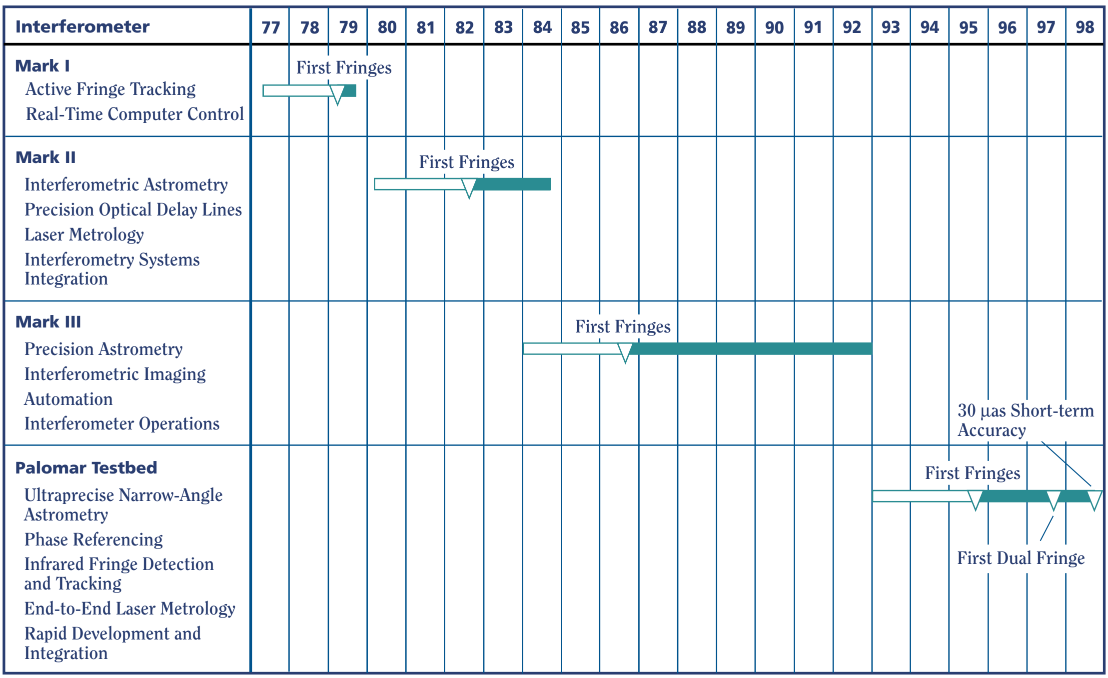
IMOS MODELING

Collector deformation due to temperature change: result of a thermal–mechanical analysis run using IMOS.

TECHNOLOGY TIMELINE
Technologies demonstrated with ground-based stellar interferometers.

the Palomar Testbed Interferometer (PTI). The use of different testbeds derives from the fact that a subset of the technologies can be tested in air at nanometer precision and at full scale, while another subset must be tested in vacuum at picometer precision, but at subscale. Those technologies associated with vibration attenuation are grouped into the SIM System Testbed; those associated with laser metrology are assigned to the Microarcsecond Metrology Testbed. PTI, an operational ground-based observatory, can observe real stars, which is necessary to validate the science data-processing software.

Ground-based stellar interferometers are invaluable testbeds for space-based systems, not only from a hardware perspective, but also with a view toward operations and scientific productivity. Members of the JPL team have built and operated a series of ground interferometers over a period of nearly 20 years. These interferometers have pioneered



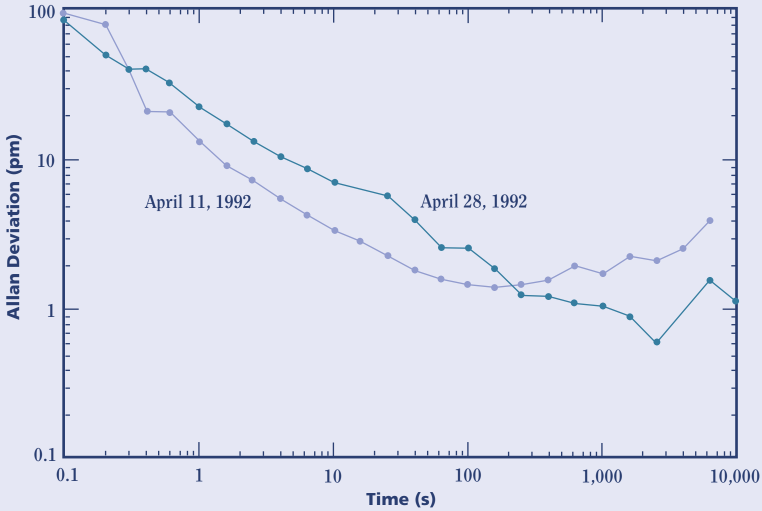
MICROARCSECOND METROLOGY TESTBED

The Microarcsecond Metrology Testbed (MAM) will demonstrate that picometer metrology components can be configured in an interferometer to measure the position of a point source to the microarcsecond level. This will be done at one-fifth scale in a 3 × 13–meter vacuum chamber. MAM uses a 1.8-meter baseline interferometer to observe an artificial star. The positions of the star and the interferometer are monitored by an external metrology system during the experiment.

The interferometer is composed of siderostats for wide-angle acquisition, fast-steering mirrors for fine guidance, a delay line for optical path control, and a beam combiner. The metrology system consists of four beam launchers: two monitoring the star, and two internal launchers monitoring the optical pathlength through the interferometer. An additional metrology experiment coexists with the MAM interferometer and metrology systems and is referred to as the "kite" because of its shape. It uses five additional beam launchers to test their stability and precision.

The interferometer includes all the functionality of the flight system in a reduced-scale and reduced-dimensionality experiment. The MAM optics, metrology system, and artificial star are placed in a vibration-isolated, thermally stabilized vacuum chamber. This eliminates index-of-refraction fluctuations in air to achieve the goal of 50-picometer optical path measurement accuracy.

Initial MAM operation is planned for late 1999 with a single-baseline, narrow-angle experiment. The artificial star will be moved over a 20-arcsecond (1-millimeter) range. The position of the star will be monitored by both the white-light interferometer and the external metrology system. The next stage of the experiment will be to increase the field of view, eventually reaching 5 degrees. Later, heaters and vibration transducers will be added to key optical components to study the effects on calibration and operation of the interferometer.



Gauge Results. *Results obtained with the null gauge.*

The MAM testbed relies on the extensive use of picometer metrology laser gauges. These gauges are currently undergoing a series of careful performance tests that will culminate with the "kite" experiment in late 1999. The fundamental feasibility of this laser-gauge technology was experimentally demonstrated in the early 1990s. Heterodyne gauges were tested both in null gauge and relative gauge configurations.

advances in interferometer architecture, algorithms, performance, automation, and scientific productivity that are directly applicable to SIM.

A series of stellar interferometers — Mark I through Mark III — was built and operated on Mt. Wilson in Southern California. The instruments were technological forerunners of PTI, funded by NASA to demonstrate the technology for ultraprecise narrow-angle astrometry. This technology is now being applied to the Keck Interferometer and the detection of exoplanets through observations of the perturbations of the parent star. Development of PTI began in December 1992. The site at Palomar Mountain was available for occupancy in May 1995; first fringes were obtained three months later, in July 1995. The instrument recently attained its performance goal of sub-50-milliarcsecond narrow-angle astrometry, over single observation times on the order of hours. Testing of multi-night astrometric measurement stability is currently under way.

PTI has a 110-meter baseline, employing 50-centimeter siderostats with 40-centimeter telescopes. It is designed as a dual-star system, using a bright target star to cophase the system in order to detect a faint astrometric reference star against which the astrometric perturbations of the bright target are measured. PTI employs four delay lines, two with physical travels of 20 meters each, and two with shorter travels for offsetting between the two stars. It works in the near-infrared, and is the first infrared interferometer to employ the active fringe-tracking technology originally developed on the Mark I. PTI also incorporates complete end-to-end laser metrology of the internal optical path from the stellar beam combiner to a corner cube located in front of the siderostat. This bias-term metrology system uses the same optical architecture as does SIM, employing the starlight beamsplitter as the metrology beamsplitter to eliminate non-common-mode measurement errors.

Perhaps the most significant benefit of PTI for SIM, besides the obvious one of building, integrating, and operating the instrument, is the implementation approach that was used. PTI was built in a highly modular manner, both with respect to the optical system and the computer control system. The computer system, which employs nine real-time, single-board computers, integrates these with a high-level communications architecture that hides most of the details associated with the large number of CPUs from the subsystem developer. This allowed developers to concentrate on the details of their subsystem, and also allowed multiple developers to work simultaneously. Modularity enabled the testing of subsystems in the lab and on the roof of the lab at JPL, so that final systems integration on the mountain took less than three months to obtain first fringes. PTI, while borrowing extensively from the Mark III, incorporated all new software. The modularity and testability of the architecture allowed a rapid development cycle. The architecture is also autonomous. As a demonstration of the degree of autonomy reached, PTI has been operated remotely from JPL, more than 160 kilometers (100 miles) away.

In the future, PTI will serve as a development platform for interferometer science data-processing software. Its narrow-

Stellar interferometers were funded by NASA to demonstrate the technology for ultraprecise narrow-angle astrometry.

PTI
The Palomar Testbed Interferometer near San Diego, California.

angle astrometry measurements are similar enough to those taken by SIM that the data-processing software developed for PTI astrometry will become the core of the SIM narrow-angle astrometry science software.

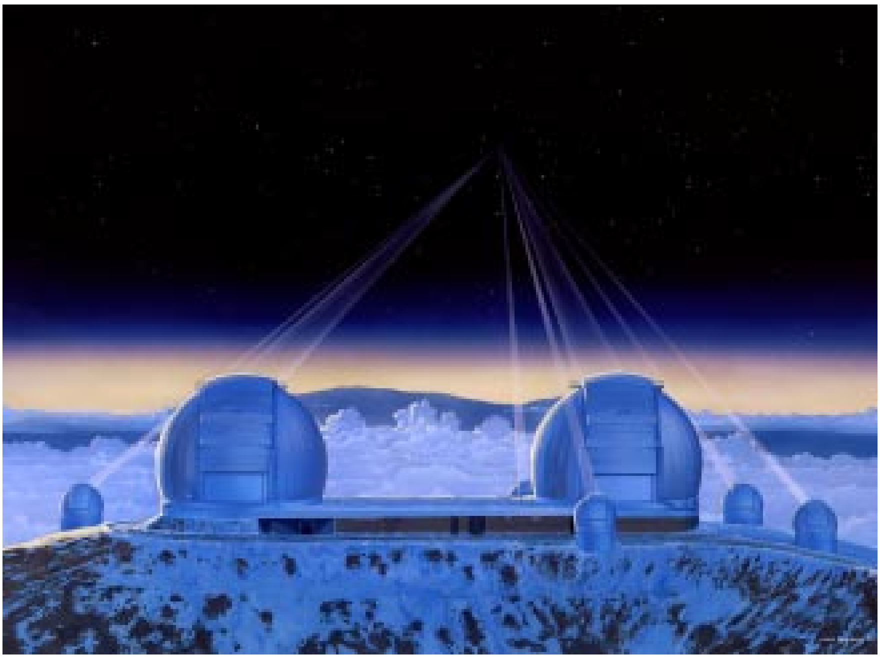
Development of the Keck Interferometer is taking place largely in parallel with the development of SIM technology. This has enabled synergistic work in at least two important areas: real-time software and starlight nulling. The Keck Interferometer and SIM will both make use of the same core software being developed by the software development team. This will benefit SIM in that another operational system will be the first to check out and run the software. In the area of nulling, thus far SIM and the Keck Interferometer have pursued development of a common nulling beam combiner. This effort is now at the point of bifurcation, where the Keck must develop hardware that operates in the infrared while SIM will build a visible-light system. Nevertheless, the two efforts will continue to share results and learn from one another.

Flight Experiments

Flight experiments will only be performed when the technology in question cannot be validated on the ground. The technology for deployable structures is considered to be relatively mature from the standpoint of scale (more than 50 meters in length), initial deployment accuracy (millimeters), and long-timescale stability over thermal loads (millimeters). But the on-orbit, short-timescale stability (above 1 hertz) of these systems in the nanometer regime is unknown.

The concern is that deployable structures are dominated by hinges, latches, and joints, all of which have the potential to exhibit stick–slip nonlinearities. This creates the possibility of "creaking" due to time-varying thermal conditions. Such creaking would likely have broad frequency content, given its impulsive nature. Thus, even if it occurs on the micrometer scale, creaking could be quite problematic for an interferometer whose actively controlled optics might not have sufficient bandwidth to track it out.

Ground-based experimental investigation of the microdynamic behavior of deployable structures is very difficult. In particular, testing in the 1-g environment suffers from the inability to per-



KECK INTERFEROMETER
The Keck Interferometer atop Mauna Kea, Hawaii. (Artist's concept.)

TECHNOLOGY DEVELOPMENT
(opposite) The SIM technology development flow.

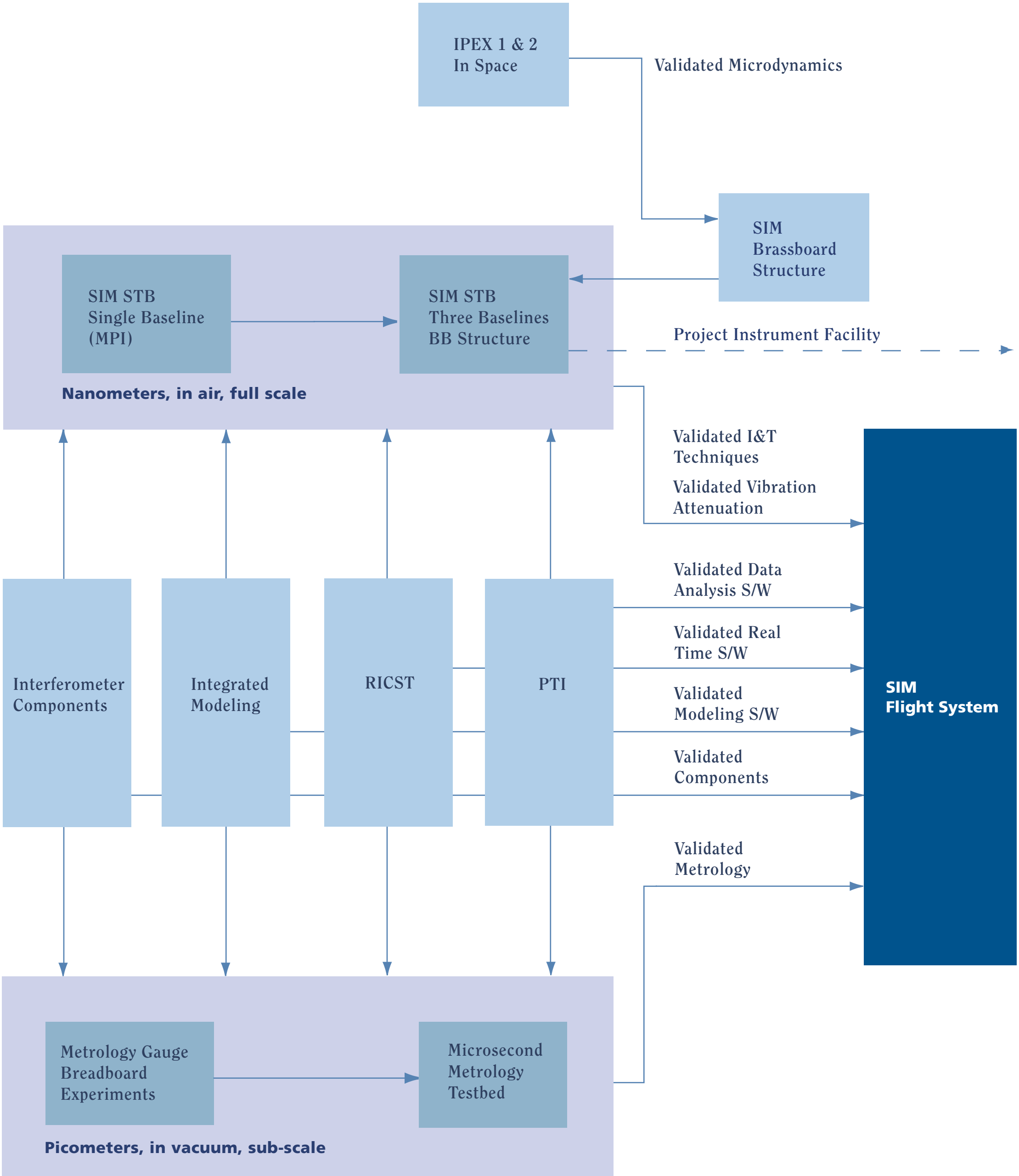
fectly remove gravity-induced internal loads from the test specimen in order to emulate on-orbit conditions. These gravity-induced "preloads" could well act to completely hide the suspected stick–slip phenomena that would be unleashed only in space. This is the motivation for conducting space experimentation to understand the microdynamics of deployable structures.

Interferometry Program Experiment-1 (IPEX-1) was the first step toward filling the microdynamics information gap. Hosted on the German Space Agency's Astro-SPAS platform, which flew on a NASA space shuttle mission in December 1996, IPEX-1 gathered 12 channels of micro-g acceleration data. During quiet periods when thrusters were not operating, accelerations on the order of 100 micro-g's were measured.

IPEX-2
IPEX-2 deployment from the space shuttle.

These data yielded an important result: the microdynamics of built-up monolithic structures like Astro-SPAS appear to be compatible with interferometer mission requirements. The successor experiment, IPEX-2, was flown in August 1997, a scant 8 months after IPEX-1. IPEX-2 consisted of an instrumented portion of a representative deployable structure. Over 60 channels of accelerometer, load-cell, and temperature data were taken during various orbital thermal conditions, including sunshade transitions and long-duration hot and cold soaks.

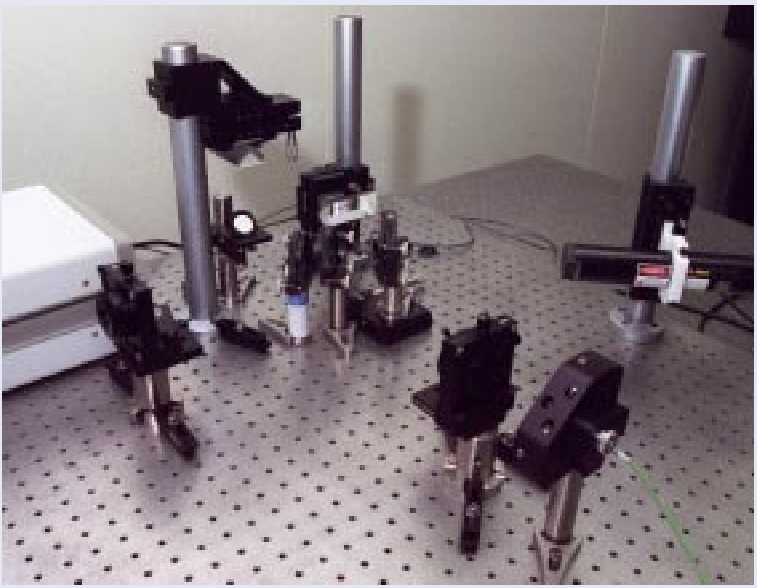
The preliminary conclusion is that deployable structures that are engineered to eliminate backlash in joints and are placed in thermally benign orbits, such as an Earth-escape orbit like SIM's, will exhibit sufficiently low levels of microdynamics to support optical interferometry. The ultimate intent is to combine the flight data with ground test measurements to develop empirically validated analytical models. This work will be carried out by JPL in conjunction with NASA Langley Research Center, and will involve university participation from the Massachusetts Institute of Technology and the University of Colorado.


IPEX 1 & 2
In Space
Validated Microdynamics
SIM
Brassboard
Structure
SIM STB
Single Baseline
(MPI)
SIM STB
Three Baselines
BB Structure
Project Instrument Facility
Nanometers, in air, full scale
Validated I&T
Techniques
Validated Vibration
Attenuation
Validated Data
Analysis S/W
Validated Real
Time S/W
Validated
Modeling S/W
Validated
Components
Validated
Metrology
Interferometer
Components
Integrated
Modeling
RICST
PTI
SIM
Flight System
Metrology Gauge
Breadboard
Experiments
Microsecond
Metrology
Testbed
Picometers, in vacuum, sub-scale

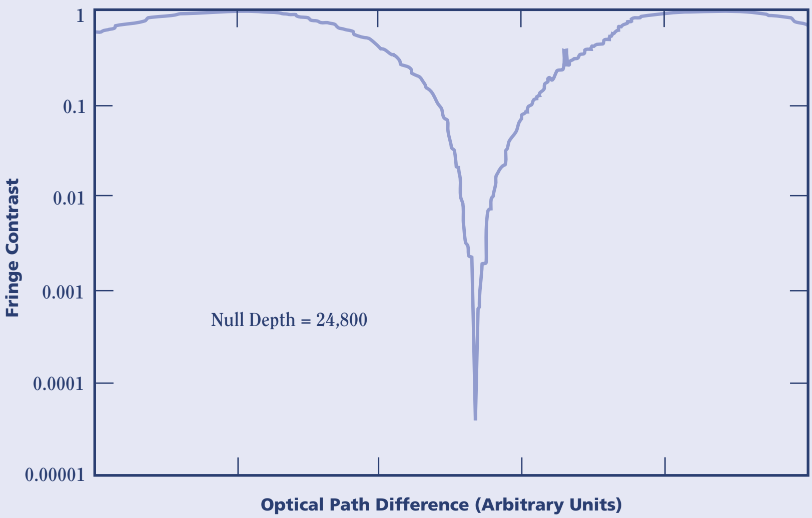
SIM

Nulling

The technology program at JPL has met an important milestone 9 months ahead of schedule. The challenge of building an instrument capable of achieving a factor of 10,000 destructive interference across a broad waveband (~20 percent) was and is considered severe. In response, two different techniques are pursued in parallel, one at JPL and the other at the University of Arizona. Prior to December 1998, each effort had achieved roughly a factor of 1,000 nulling on laser light and a factor of 20–40 on white light. In December 1998, the JPL effort achieved a factor of 25,000 null on a laser diode (~0.5-percent bandpass), a milestone that was expected to require a more sophisticated apparatus and an additional 9 months of schedule. We are pushing on to duplicate this result on broadband light and thereby establish the basic feasibility of SIM nulling.



Nulling Tests. *JPL bench-top nulling apparatus.*



Nulling Success. *Optical path delay sweep producing factor of 25,000 null.*

Real-Time Software

In early January 1999, the real-time software development team met a major milestone with the incorporation of advanced autonomy capability, the NASA Ames Research Center–developed Remote Agent, into the prototype interferometer control code. Originally scheduled to fly on NASA's New Millennium Deep Space 1 Mission (launched in October 1998), the Remote Agent is a mature state-of-the-art software package that contains artificial intelligence and expert system capability. The January milestone demonstrated full Remote Agent optical delay-line control from power-up to slew, fringe acquisition, and tracking.

Industry Partnership

The two industry partners, Lockheed Martin and TRW, have been fully integrated into the technology development effort. In addition to general across-the-board support, each partner has lead responsibilities for a subsystem-level testbed — Lockheed Martin leads the Thermal Optical Mechanical testbed to demonstrate picometer mechanical stability of optics at millikelvin temperature changes, and TRW leads the substructure test article to develop critical elements of the precision structure for deployment and thermal deformation testing.